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Evidence on the Origin of Ergospheric Disk Field Line Topology in Simulations of Black Hole Accretion

Brian Punsly
4014 Emerald Street No.116, Torrance CA, USA 90503
ICRANet, Piazza della Repubblica 10 Pescara 65100, Italy,
E-mail: brian.punsly@verizon.net or brian.punsly@comdev-usa.com

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ABSTRACT
This Letter investigates the origin of the asymmetric magnetic field line geometry in the ergospheric disk (and the corresponding asymmetric powerful jet) in 3-D perfect magnetohydrodynamic (MHD) numerical simulations of a rapidly rotating black hole accretion system reported in Punsly et al (2009). Understanding, why and how these unexpected asymmetric structures form is of practical interest because an ergospheric disk jet can boost the black hole driven jet power many-fold possibly resolving a fundamental disconnect between the energy flux estimates of powerful quasar jets and simulated jet power (Punsly 2011). The new 3-D simulations of Beckwith et al (2009) that were run with basically the same code that was used in the simulation discussed in Punsly et al (2009) describe the "coronal mechanism" of accreting poliodal magnetic flux towards the event horizon. It was determined that reconnection in the inner accretion disk is a "necessary" component for this process. The coronal mechanism seems to naturally explain the asymmetric ergospheric disk field lines that were seen in the simulations. Using examples from the literature, it is discussed how apparently small changes in the reconnection geometry and rates can make enormous changes in the magnetospheric flux distribution and the resultant black hole driven jet power in a numerical simulation. Unfortunately, reconnection is a consequence of numerical diffusion and not a detailed (yet to be fully understood) physical mechanism in the existing suite of perfect MHD based numerical simulations. The implication is that there is presently great uncertainty in the flux distribution of astrophysical black hole magnetospheres and the resultant jet power.

Key words: Black hole physics — magnetohydrodynamics — galaxies: jets—galaxies: active — accretion, accretion disks

The ultimate nature of the power output of a black hole magnetosphere is highly dependent on two poorly understood circumstances, the source of plasma injection on the magnetic field lines that thread the event horizon and the fate of accreted vertical magnetic flux (Punsly and Coroniti 1990a,b). In the past eight years, the use of perfect magnetohydrodynamic (MHD) numerical simulations have been developed in the scientific community to help understand these issues. In order to establish and maintain the event horizon magnetosphere, the simulations must rely on the numerical artifice of a mass floor, local mass injection to establish a minimum density. In spite of some discussion of anecdotal mass floor examples, perfect MHD simulations are not likely to resolve the first issue since a mass floor violates rest-mass and energy - momentum conservation and necessarily contradicts the perfect MHD assumption (McKinney 2006b). However, recently MHD simulations have shed some light on the second point. The mystery of how magnetic flux was accreted to the black hole in MHD numerical simulations was revealed in Beckwith et al (2009) through their meticulous high resolution numerical work. In this Letter, the insight provided by Beckwith et al (2009) is used to explain the strange ergospheric disk field topology seen in the simulations reported in Punsly et al (2009) that resulted in powerful one-sided jets that dominate the total energy output in the jetted system with a location that changed hemispheres in different time snapshots (Punsly 2007a,b).

The fate of accreted flux is perhaps the most critical issue in understanding the power source for black hole driven jets. It was noted in Punsly and Coroniti (1990b), that if vertical, magnetic flux accretes, it is not clear where it ends up. It was argued that reconnection of vertical flux would be

determinant to the final magnetic field configuration since the black hole is effectively a sink with infinite capacity for mass, but with a very limited capacity to accept magnetic flux. One possible field configuration that could result from reconnection produced a disk in the ergosphere that can drive powerful jets. If this happens, the power source for the jet drastically increases in efficiency, so this configuration is of profound interest in AGN (Nemmen et al 2007; Punsly 2011). However, there is much scientific uncertainty in the reconnection geometry and rate expected in an accretion flow near a rapidly rotating black hole, since our experimental experience is based on very different environments, the solar corona, the solar wind, the Earth magnetosphere and magneto-tail, and magnetic confinement devices for thermonuclear fusion. The situation was further complicated by the argument that the existence of coherent vertical flux within the dense accreting gas is inhibited by the turbulent magnetic diffusivity of the plasma (van Ballegooijen 1989; Lubow et al 1994). Thus, it was not even clear if the notion of a large scale field associated with an accretion flow was viable.

However, recent numerical simulations have shown that vertical flux accretion can occur, but not by diffusing through the disk, but by a two step process called the "coronal mechanism". The first step is the transport towards the black hole of an inwardly stretched, disk-anchored, poloidal loop through the low turbulence, coronal layer just above the disk, the "hairpin" field in Beckwith et al (2009). This coronal transport is similar to the mechanism proposed in Rothstein and Lovelace (2008), but see Beckwith et al (2009) for some dynamical differences. Then loops of magnetic field in the inner accretion flow reconnect with the half of the "hairpin" at mid-latitudes, allowing it to contract into the black hole, leading to one sign of field threading the black hole (see section 2). Reconnection is apparently "necessary" for vertical flux accretion in all the numerical simulations of this family Beckwith et al (2009); Hawley and Krolik (2006); McKinney and Blandford (2009), but the geometry of the reconnection site is very different than what was described in Punsly and Coroniti (1990b). In spite of this geometric difference, an ergospheric disk does form in some simulations. In the following, the coronal mechanism is shown to naturally explain the asymmetric magnetic field observed in 3-D simulations of the ergospheric disks (Punsly et al 2009).

This work derives from a family of simulations based on a constrained transport MHD code on the Kerr spacetime background that has been described numerous times in the literature, so this is not reproduced here (De Villiers and Hawley 2003a; De Villiers et al 2003b, 2005; Hirose et al 2004; Krolik et al 2005; Hawley and Krolik 2006; Beckwith et al 2008). The particular simulation, KDJ, discussed in Punsly et al (2009) was described in detail in Krolik et al (2005); Hawley and Krolik (2006), which the reader should consult for particulars. KDJ simulates accretion onto a rapidly rotating black hole with an angular momentum per unit mass of a = 0.99 M in geometrized units. This Letter focuses on the very complicated twisted topologies that are involved in the reconnection events in the simulation.

1 FIELD LINE TOPOLOGY IN THE ERGOSPHERIC DISK

A surprising feature of 3-D MHD numerical simulations is that the ergospheric disk was threaded mainly by the type I field lines instead of type III field lines in the nomenclature introduced in Punsly et al (2009). In the left hand panel of Figure 1, the type I vertical magnetic field lines emerge from the inner equatorial accretion flow. The false color plot is a contour map of a 2-D cross-section of the density in Boyer-Lindquist coordinates expressed in code units. The interior of the inner calculation boundary (just outside of the event horizon) is grayish-white. These field lines are distinguished by connecting to the Poynting jet in one hemisphere only, with the other end spiraling around within the accreting gas in the opposite hemisphere. Another distinguishing feature of a type I field line is that the azimuthal direction of the magnetic field changes direction as the field line crosses the midplane of the accretion flow. It was expected in Punsly and Coroniti (1990b) that the direct advection of magnetic flux would produce the type III field topology depicted in the right hand frame of Figure 1. But these were rare in the 3-D simulation reported in Punsly et al (2009). Unlike the type I field lines, the type III field lines connect to both sides of the bipolar jet.

One should consult Figure 3 of Punsly et al (2009) to appreciate the physical significance of the one sided type I field lines from the ergopsheric disk. These field lines directly equate to a powerful jet of Poynting flux. When this jet forms, it swamps the power output from the event horizon (Punsly 2007a,b). In fact, it even suppresses the event horizon jet power to some degree (Punsly 2011).

2 RELEVANT ASPECTS OF THE CORONAL MECHANISM

In this section, the coronal mechanism is reviewed and asymmetric variations in the process are noted that are relevant to the following. The coronal mechanism was detailed in Figure 11 of Beckwith et al (2009). Some important geometric simplifications were implemented in Beckwith et al (2009) that greatly improved the clarity of presentation. In that paper, the primary focus was on detailed discussions of symmetric pairs of "hairpin" field lines, where one approaches from just above the accretion disk from the North and a matching "hairpin" field line approaches from the South. Furthermore, a non-rotating black hole was chosen so there is minimal azimuthal twisting near the event horizon. Ostensibly, for the sake of simplicity of presentation, all the 3-D data was averaged over azimuth in Beckwith et al (2009), so there were simple field line topologies like closed 2-D poloidal loops in the accretion disk (see their Figure 11).

After the leading edge of the hairpins have penetrated the event horizon, reconnection occurs in the equatorial portion of the hairpin with a closed 2-D loop. This leads to an increase in the magnetic flux in the accretion flow vortex, or "funnel", in the polar region beyond the event horizon radius in both hemispheres.

It is noted here that there are two intriguing aspects of the field line evolution presented in Beckwith et al (2009) that should be relevant to 3-D field line reconnection in the Kerr geometry.

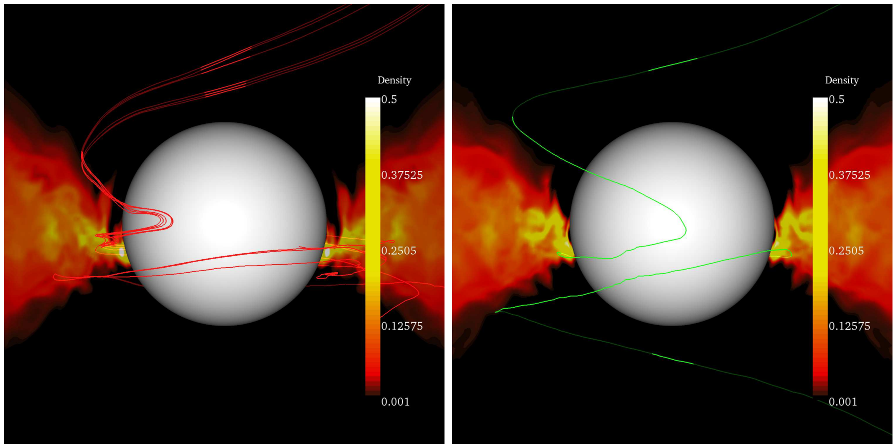

Figure 1. Plots of ergospheric disk field lines in the simulation, KDJ, from Punsly et al (2009). For details of how the field lines were plotted and the false color 2-D density cross section, please refer to that paper. It was expected that the type III ergospheric disk field line topology (on the right) would dominate the vertical flux through the ergospheric disk. Instead 3-D MHD numerical simulations found very few type III field lines, but many type I field lines (on the left). It should be noted that the images are 3-D. They were created in the 3-D visualization tool, Paraview 3.3, as 3-D images and the "camera" is placed in the equatorial plane (i.e., if the y-axis points toward the camera, the gas density is plotted in the x-z plane). The field lines that pass behind the x-z plane are made darker (i.e. the x-z plane is partially opaque, 75%) to make it easy to distinguish them from the magnetic coils in front of the x-z plane. However, near the poles they are not darker because a conical region of the numerical grid is excised in that region (therefore, there are no points in the x-z plane above the poles of the horizon and no opacity) as a numerical expedience as discussed in Hawley and Krolik (2006) and Punsly et al (2009).

(i) There is not always symmetry in the hairpin accretion between the northern and southern hemispheres. A cluster of field lines in a "hairpin" configuration often approach from one hemisphere at a time. This is manifested in the online animation for Beckwith et al (2009), especially around 23 seconds, where one sees an excess of organized flux in the funnel, in the southern hemisphere of the event horizon. This asymmetry also appears to a much lesser degree in Figure 11 of Beckwith et al (2009). Note that the animation that accompanies the 2-D simulation around a rapidly spinning Kerr black hole in Beckwith et al (2008) also shows asymmetric hairpin accretion. This supports the notion that asymmetric hairpin field line accretion is not dependent on spin. This does not mean that reconnection will proceed similarly in 2-D and 3-D and independent of spin. Instead the simulations show only that the potential pre-reconnection field configuration of asymmetric accretion of hairpin field lines seems to occur in either 2-D or 3-D and for high spin and low spin.

(ii) Some of the hairpins can actually be buoyant near the horizon and move away from the black hole, never penetrating the horizon (eg., the hairpin $\approx 30^{\circ}$ below the equator in Figure 11 of Beckwith et al (2009) moves outward between t= 14600 M and t= 14640 M)

3 RECONNECTION GEOMETRY IN THE 3-D ACCRETION NEAR RAPIDLY ROTATING BLACK HOLES

The reconnection aspect of the "coronal mechanism" described in Beckwith et al (2009) relies on the topology of poloidal loops in the inner accretion disk. However, in the case of interest here, 3-D around a rapidly spinning black hole, almost all the flux in the inner accretion flow is twisted up into toroidal coils (Hirose et al 2004; Punsly et al 2009). There are no simple poloidal loops in 3-D like there were in the azimuthally averaged data in Figure 11 of Beckwith et al (2009). Since topology is critical to reconnection, the 2-D expedience is not implemented here for the sake of accuracy and the expense of complexity. The analog of a 2-D poloidal loop in the Schwarzschild geometry in the 3-D Kerr (rotating black hole) geometry would seem to be one of the many twisted coils that permeate the accretion flow Hirose et al (2004); Punsly et al (2009). The "loop" from t = 9840 M (in geometrized units) of KDJ that is plotted in white in the left hand frame of Figure 2 is typical of most of the field lines in the inner accretion disk for high spin black holes. It spirals near the black hole then as it expands vertically, it leaves the disk and penetrates the corona. The twisted loop connects to large distances through the corona, presumably closing far away. There are variations of this topology in which one end of the coil stays in the disk while the other end permeates the corona or event horizon (Punsly et al 2009).

There are no fine time resolution snapshots of the simulation KDJ (the data is sampled every 80 M), so we cannot see the asymmetric type I field lines of Figure 1 forming. There is only circumstantial evidence as to the chain of events:

(i) Most of the disk field lines in KDJ are twisted coils near the event horizon that can have significant random inflections due to turbulence and never leave the disk or corona (Punsly et al 2009; Hirose et al 2004).

(ii) In KDJ, large vertical flux bundles are entrapped in the inner regions of the accretion flow tending to be far more pronounced in one hemisphere (Punsly et al 2009).

(iii) In KDJ, the ergospheric disk flux shows no tendency for a preferred hemisphere. They can be in either hemi-

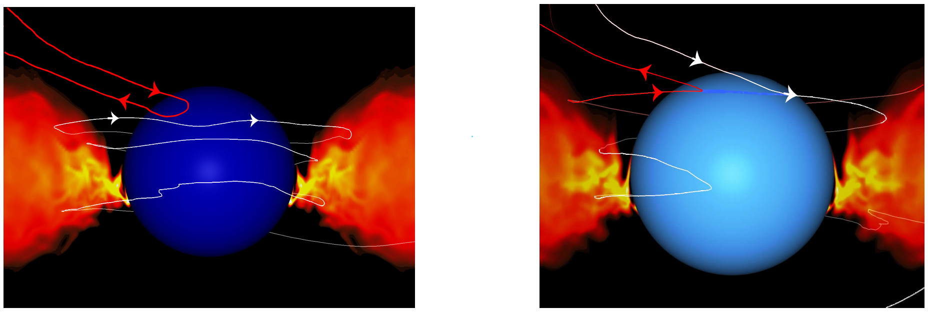

Figure 2. A potential reconnection site in KDJ is displayed in the left hand frame. The red field line is the accreting, slightly twisted coronal hairpin. The white field line is a typical twisted structure that is the 3-D equivalent of a poloidal loop in a 2-D Schwarzschild representation. The inner calculational boundary is blue. The post reconnection topology is depicted in the right hand frame. The red curve is a buoyant hairpin. The white curve is a type I field line that threads the ergospheric disk as in Figure 1.

sphere or both hemispheres in an individual time snapshot (Punsly et al 2009).

(iv) The animations of simulations show that significant poloidal flux can accrete to the inner regions of the accretion flow through the corona in the form of hairpins in an episodic fashion (Beckwith et al 2008, 2009).

(v) These hairpins can arrive at the inner edge of the flow in asymmetric north/south configurations (Beckwith et al 2008, 2009).

(vi) The topology of the poloidal flux near the event horizon was shown to be determined by reconnection with simple poloidal loops in 2-D azimuthally averaged data (Beckwith et al 2009).

(vii) Figure 11 of Beckwith et al (2009) not only shows the asymmetric accretion of hairpins to the event horizon, but also that some hairpins near the black hole can actually become buoyant and move away from the black hole.

These seven facts can be used to consider the time evolution in the twisted geometry of KDJ that results in the type I field line topology in Figure 1. Figure 2 simulates the most plausible scenario based on these seven results above which is used as a surrogate for actual fine time scale data sampling. The left hand frame shows a typical twisted accretion disk coil in white being approached by a coronal hairpin in red near the black hole. Notice that the coronal hairpin is azimuthally twisted in KDJ. Reconnection is very complicated in a twisted 3-D environment and is not well understood (Pontin et al 2011). However, the configuration as drawn forms a natural reconnection site (an X-point). We expect both types of field lines in Figure 2 to exist from points 1, 4 and 5 above. The elements required for the pre-reconnection geometry in the left hand frame of Figure 2, commonly occur in this family of simulations. Thus, it is reasonable to expect that these field configurations coexist in proximity at various times and these potential reconnection sites should not be rare. However, the reconnection rate in such a complicated geometry that does not proceed by a physical mechanism, but through numerical diffusion, is very uncertain. By points 2, 3 and 6 above, reconnection must have occurred in KDJ as depicted in the right hand frame of Figure 2. The white curve in the right hand frame is poloidal flux through the equatorial plane of the ergosphere in one hemisphere in analogy to the left hand frame of Figure 1 and the red curve would be a buoyant hairpin field line that moves out in the corona consistent with point 7.

A significant difference between the topology resulting from the reconnection in Figure 2 compared to that in Figure 11 of Beckwith et al (2009), is that in Figure 2 the reconnection is happening before the hairpin penetrates the event horizon and in Figure 11 of Beckwith et al (2009) it occurs after the hairpin penetrates the horizon. This indicates that the coherent flux transport rate combined with the reconnection rate and twisted 3-D field line geometry (which affects the reconnection rate) might determine if a field line penetrates the event horizon or the inner accretion flow when and if reconnection occurs. The final field line topology depends on the balancing of reaction rates (reconnection and transport) as well as internal dynamics (that affect field line shape) that are determined by the numerical simulation.

4 DISCUSSION

The Letter shows that the "coronal mechanism" for flux transport in simulations of black hole accretion provides a plausible explanation for the one sided ergospheric disk field lines in the high spin 3-D simulation KDJ. It therefore explains the strange phenomenon observed in KDJ that the black hole driven jet Poynting flux was very one sided, jumping from side to side and emanating primarily from the ergospheric disk.

An otherwise almost identical simulation to KDJ that includes additional artificial diffusion terms in the equations of continuity, energy conservation, and momentum conservation (as described in De Villiers (2006)) do not show these one sided ergospheric disk structures Punsly (2011). This is seems to indicate a change in the the reconnection process that is driven either directly or indirectly by the numerical diffusion. In support of this interpretation, the force-free simulations of an initially uniform field in Komissarov (2004) show magnetic flux threading the ergospheric equatorial plane near the black hole, yet the same initial state that is time evolved in a different force-free code with a slower ansatz for the reconnection rate shows no magnetic flux threading the equatorial plane near the black hole (McKinney 2006a). The implication is that the global topology of the black hole magnetosphere is highly dependent on the time evolution driven by reconnection. This is not a trivial circumstance because in MHD simula-

tions reconnection is dependent on numerical diffusion. The situation is rendered even more ambiguous by the complicated twisted magnetic field line geometries in 3-D simulations around rapidly rotating black holes (eg. Figure 2). The complications of far less intricate 3-D field line topology have been recognized in solar and planetary physics (Pontin et al 2011; Wilmot-Smith et al 2010). Similarly, some detailed numerical modeling has shown the need for 3-D to properly describe reconnection (Kowal et al 2009; Kulpa-Dybel et al 2010). Furthermore, in high energy environments radiation effects might also be crucial for a proper treatment Uzdensky (2011). This might be relevant because radiation is not formally considered in these MHD codes. In summary, there are many potential sources of uncertainty in the reconnection induced topology in these simulations.

It should be noted that in principle, the choice of coordinates (eg. Boyer-Lindquist, as in the simulations discussed here, or Kerr-Schild) should be irrelevant to the results obtained. What is likely more relevant is the grid scale and sources of numerical diffusion in the solution methodology. A very basic consideration is that once a field line that is frozen-in to the plasma is accreted through the event horizon (technically, the inner calculational boundary that is just outside the event horizon in Boyer-Lindquist coordinates), it should be unable to migrate out of the horizon by moving outward into the equatorial plane if causality is maintained by the frozen-in plasma inside the horizon. Field lines can only be extracted from the horizon by local reconnection, not diffusion back into the equatorial plane. As such, a black hole saturated with magnetic flux is a nontrivial "boundary condition" for further magnetic flux accretion of the same orientation. For example what happens when there is repeated injection of magnetic flux as in the simulations of Igumenshchev (2008). The suite of simulations considered here have a finite amount of flux (either vertical or the leading edge of accreting loops) that accretes towards the black hole and a boundary condition that flux cannot leave or enter through the outer boundary. However, if that boundary condition is changed to be one of continuous injection of flux then the magnetic topology might change near the black hole. In particular, Beckwith et al (2009) suggest that the funnel and horizon field strength is set by the gas and magnetic pressure in the disk and Tchekhovskoy et al (2010) claim that it is set by the ram pressure in the disk. Once this very finite value is achieved, what happens when more flux is injected into the accretion stream and approaches the horizon? Does this preferentially move the reconnection sites out to near the mid plane of the ergosphere? This might raise the power level to be consistent with the more powerful radio loud AGN (Nemmen et al 2007; Punsly 2011).

In the absence of more robust treatments of reconnection, this study suggests two new simulations that are achievable with the present numerical codes. One would be to rerun KDJ with the original code, but with high density time sampling for a portion of the run so that we can see how the ergospheric disk flux gets established. It would also be an interesting simulation to explore the possibility of continuous vertical flux injection from the outer boundary around rapidly rotating black holes to see if the pattern of reconnection changes and if the magnetospheric distribution of flux changes, possibly enhancing the ergospheric disk. In the future, more realistic reconnection in the presence of resistivity needs to modeled near black holes as in Palenzuela et al (2009). One might also find environments suitable for reconnection in the ergospheres of other simulation geometries that can produce relativistic jets. For example, the collisions of black holes as discussed in Palenzuela et al (2010) or the inner regions of a tilted accretion disk as modeled in Fragile et al (2007) are fertile areas to pursue.

REFERENCES

Beckwith,K., Hawley,J., Krolik,J. 2008, ApJ **678** 1180

Beckwith,K., Hawley,J., Krolik,J. 2009, ApJ **707** 428

Blandford, R. D. and Payne,D., 1982, MNRAS **199** 883

De Villiers, J., Hawley, 2003, ApJ **589**, 458

De Villiers, J-P., Hawley, J., Krolik, 2003, ApJ **599** 1238

De Villiers, J-P., Hawley, J., Krolik, J.,Hirose, S. 2005, ApJ **620** 878

De Villiers, J-P. 2006, astro-ph/0605744

Fragile, P.C., Blaes,O., Anninos, P., Salmonson, J. 2007, ApJ, **668** 417

Hawley, J., Krolik, K. 2006, ApJ **641** 103

Hirose, S., Krolik, K., De Villiers, J., Hawley, J. 2004, ApJ **606**, 1083

Igumenshchev, I. V. 2008, ApJ **677** 317

Komissarov, S. 2004, MNRAS **350** 447

Krolik, K., Hawley, J., Hirose, S. 2005, ApJ **622**, 1008

Kowal, G.; Lazarian, A.; Vishniac, E.; Otmianowska-Mazur, K. 2009, ApJ **700** 63

Kulpa-Dybel, K.; Kowal, G.; Otmianowska-Mazur, K.; Lazarian, A.; Vishniac, E. 2010 A & A **514** 26

Lubow, S. H., Papaloizou, J. C. B and Pringle, J. E. 1994, MNRAS **267** 235

McKinney, J. 2006a, MNRAS **367** 1797

McKinney, J. 2006b, MNRAS **368** 1561

McKinney, J., Blandford, R. 2009, MNRAS Letters **394** 126

Nemmen, R.,Bower, R., Babul, A., Storchi-Bergmann, T. 2007, MNRAS **377** 1652

Palenzuela, C., Lehner, L., Reula, O. and Rezzolla, L. 2009, MNRAS **394** 1727

Palenzuela, C., Lehner, L., Liebling, S.L. 2010, Science **329** 927

Pontin, D.I. 2011, Advances in Space Research **47** 1508

Punsly, B., Coroniti, F.V. 1990a, ApJ **350** 518

Punsly, B., Coroniti, F.V. 1990b, ApJ **354** 583

Punsly, B. 2007, ApJL **661**, 21

Punsly, B. 2007, MNRAS Letters **381**,79

Punsly, B., Igumenshchev, I. V., Hirose, S. 2009, ApJ **704**, 1065

Punsly, B. 2011, ApJL **728**, 17

Rothstein, D. and Lovelace, R. V. E. 2008, ApJ **677** 1221

Tchekhovskoy, A., Narayan, R. and McKinney, J. 2010, ApJ **711** 50

Uzdesnky, D. 2011, Space Sci Rev, DOI 10.1007/s11214-011-9744-5 (published online 25 February 2011) http://xxx.lanl.gov/abs/1101.2472v1

van Ballegooijen, A. A. 1989, in ASSL Vol. 156 **Accretion Disks and Magnetic Fields in Astrophysics**, ed. G. Belvedere (Dordrecht: Kluwer Academic Publishers), 99

Wilmot-Smith, A.L., Pontin, D.I., Hornig, G., 2010, A & A **516** A5